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Title: A Multiscale/Cohesive Zone Model for Composite Laminate Impact Damage

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ABSTRACT

Interface damage mechanics, or cohesive zone models, have been developed over the last decade as a method of modeling crack growth in a material or debonding between two different materials. These methods have alleviated many of the numerical problems inherent in crack modeling, including the large length scale difference between crack fronts and crack areas, stress singularities, and the adaptation of crack propagation criteria to non-linear materials. Cohesive zone models can also predict crack initiation at any number of predetermined possible crack locations. However, researchers have also found that numerical instabilities in the solutions emerge if the finite element mesh is too coarse relative to the crack process radius. Consequently, these have been practical only for very small structures, on the order of tens of millimeters, without the use of supercomputers.

We will show that changing the order of numerical integration of the interface properties independently from their spatial discretization solves this convergence problem and in most cases decreases the total computation time, allowing for simulations of much larger structures. We will also show how these results are incorporated into our multilength scale model for predicting impact damage in laminated composite plates.

Keywords: composites, cohesive zone models, impact damage

INTRODUCTION

Damage in laminated composites, particularly damage caused by low velocity impact, can significantly degrade the mechanical properties of the component with very little external evidence of damage. A project is underway at Los Alamos National Laboratories to detect damage initiation and provide real-time information about the remaining useful life of damaged composite components. An important aspect of this project is the development of simulation capability to relate measurable quantities to damage and structural integrity to reduce the need for expensive and time-consuming experiments.

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Damage prediction in composites can be very difficult because there are often multiple interacting local damage modes. Simulation is further complicated by the fact that damage modes such as

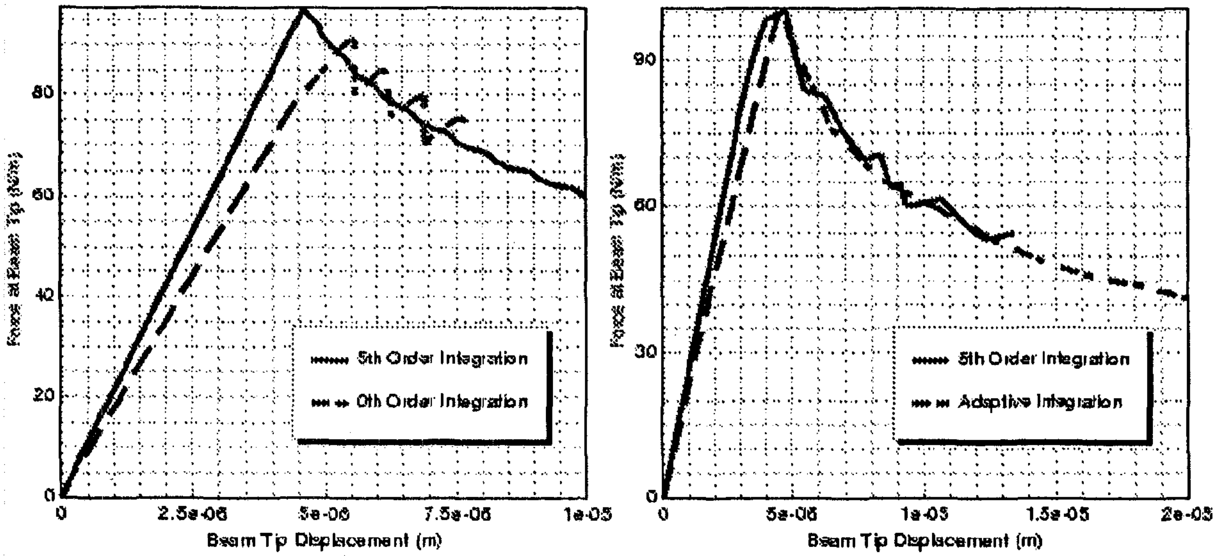

Figure 1 Double cantilever beam quasi-static mode I crack propagation results.

delamination, ply splits, transverse matrix cracks, and fiber breaks typically occur on much smaller length scale than structural detail.

MODELING APPROACH

For the prognosis of damage in the composite system in this study, delamination and ply splits have been identified as the most important damage modes in the initial impact damage and in subsequent fatigue damage. Since both of these damage modes are cracks, a cohesive zone model for each is incorporated into a finite element model for the composite plate.

The composite laminate used in this study has a [6(0/45/-45/90)]s quasi-isotropic layup. The plies are .005 inches thick, and the laminate is 2 feet by 2 feet. A finite element model of the entire plate that resolved the plies would therefore have a prohibitively large number of elements, nodes, and degrees of freedom, especially when it is considered that many simulations are required to sample the parameter space for the predictive model. Therefore, a multilength scale simulation technique is used to reduce the computational cost without a loss in small-scale damage detail.

EFFECT OF INTEGRATION ORDER

Cohesive zone models have been used as an effective means to simulate both dynamic and quasi-static crack propagation[1][2][3][4]. However, most simulations with cohesive zone models have been limited to very small structures. This is because numerical errors increase as the size of the elements becomes large relative to the length scale of the cohesive zone. These errors can obscure the true solution and even cause the nonlinear solver to fail.

These numerical errors can be reduced by using a higher-order integration algorithm to integrate the cohesive zone properties over the crack area around the crack front. The higher-order algorithm integrates the functions by sampling at more points, thereby integrating more accurately the area with the highest gradients in traction between the crack faces.

Figure 1a shows the force vs. displacement results at the tip of a double cantilever beam quasi-static test case. The 0^{th} order integration (sampled at nodes) clearly shows the erratic solution jumps that characterize large integration errors in the cohesive zone model. For this simulation, the 5^{th} order integration (sampled at 3 Gauss points in each direction) sufficiently reduces the errors and the solution jumps are eliminated. For a coarser mesh (Figure 1b,) with element lengths 3.33 times larger than those of Figure 1a, even the 5^{th} order algorithm has noticeably large integration errors. The adaptive integration algorithm gives better results because the integration error may be made arbitrarily small with a sufficiently large number of integration points. The computation time is greater; but it is only slightly greater because the higher-order integration is only applied at the crack front, where it is most needed. The use of adaptive higher-order integration algorithm usually allows a much coarser mesh than is possible with a fixed-order algorithm, which generally reduces the total computation time considerably.

MULTILENGTH SCALE

Building on previous work on multilength scale plate theory[5], a displacement-based finite element model for each subelement k within a superelement is augmented with displacement fields that are the superposition of a global and a local displacement field.

$$u^{(k)} = \underline{u}_{l(k)} + U_G = \underline{n}_{i(k)}\underline{q}_i + N_j Q_j \tag{1}$$

The displacement fields are therefore functions of both local (subelement) and global (superelement) degrees of freedom. The local and global degrees of freedom must be orthogonal to each other so that together they form an orthogonal basis.

Finite element software typically uses only local fields within each element. The multilength scale model must combine a global field that spans multiple subelements with the local displacement fields. This is conveniently accomplished by assuming that the fields defined by the original finite element shape functions ($n_{i(k)}q_i$) are the sum of the global field (N_jQ_j) and an undetermined local field ($\underline{n}_{i(k)}\underline{q}_i$) which is orthogonal to it. The orthogonality condition is then derived in terms of the combined field and enforced so that the original assumption holds true.

$$u^{(k)} = \underline{n}_{i(k)}\underline{q}_i + N_j Q_j = n_{i(k)} q_i \tag{2}$$

The condition for orthogonality over the subelement volume becomes

$$\int u_{l(k)} U_G \, dV^{(k)} = \int (n_{i(k)} q_i - N_j Q_j)\, N_j Q_j \, dV^{(k)} = 0. \tag{3}$$

These orthogonality conditions must hold for all values of the global degrees of freedom. When the variation of (3) is set to zero and the integrals are evaluated, there is a linear relationship between the local and global degrees of freedom,

$$A^{(k)} q = B^{(k)} Q \tag{4}$$

where

$$A_{ij(k)} = \int N_i \, n_{j(k)} dV^{(k)} \qquad B_{ij(k)} = \int N_i N_j \, dV^{(k)}. \qquad (5)$$

In this form, the orthogonality constraints can be easily implemented as multiple point constraints in a finite element model. The local degrees of freedom within each superelement are then solved with the constraints imposed by the global degrees of freedom. The global degrees of freedom are solved separately, with the influence of the local degrees of freedom entering as contributions to the global nodal forces (See Figure 2.) This separation of the length scales allows for a computationally efficient, recursive finite element simulation which is possible to implement with existing finite element software.

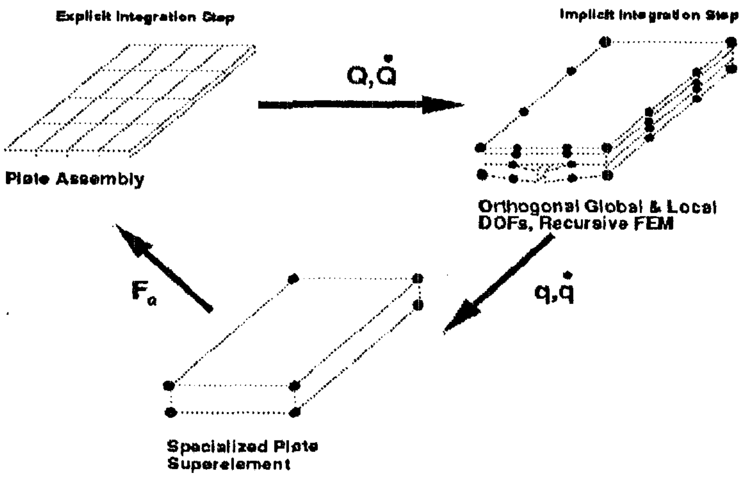

Figure 2 Multilength scale finite element solution procedure.

CONCLUSIONS

The simulation of impact damage in laminated composite plates is complicated by the large differences in length scale and the highly nonlinear local behavior of various types of fracture. These challenges are addressed in this model by a combination of adaptive higher-order cohesive zone models and a multilength scale finite element model. Both of these modeling approaches are implemented with existing finite element software, and together they provide a framework for efficient and accurate simulation of interacting damage modes.

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